Agricultural and Forest Meteorology 201 (2015) 8–16

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Radiation contributed more than temperature to increased decadal autumn and annual carbon uptake of two eastern North America mature forests

Alemu Gonsamo[a,b,*], Holly Croft[b], Jing M. Chen[b], Chaoyang Wu[c], Norma Froelich[d], Ralf M. Staebler[e]

[a] International Institute of Earth System Science, Nanjing University, Nanjing 210093, Jiangsu, China
[b] Department of Geography and Program in Planning, University of Toronto, Toronto, ON, Canada M5S 3G3
[c] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[d] Earth, Environmental and Geographical Sciences Department, Northern Michigan University, Marquette, MI 49855, USA
[e] Air Quality Processes Research Section, Environment Canada, Toronto, ON, Canada M3H 5T4

ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 3 November 2014
Accepted 9 November 2014

Keywords:
Borden forest
Carbon uptake phenology
Climate change
Harvard forest
Land surface phenology
Photosynthetically active radiation

ABSTRACT

The eastern North America mature deciduous forests are increasing their carbon (C) sink, which is believed to be due to a longer growing season. In this study, we investigated the impacts of land surface phenology (LSP) and carbon uptake phenology (CUP) on the net ecosystem productivity (NEP) of the two longest-running flux tower sites in the region. Our results show that there is no trend in the start (SOS), end (EOS), and length of growing season (LOS) at both sites; nor do they explain the interannual and long-term trend in NEP. We found no evidence for a changing growing season and cannot attribute the increasing C sink to growing season length. However, there is strong trend in end (ECU) and length of net positive carbon uptake (LCU) period. ECU is delaying and LCU is getting longer, and they both explain the interannual and long-term trends in NEP. There is increasing trend of photosynthetically active radiation (PAR) at both sites in line with increasing NEP. PAR is contributing the most both to NEP and ECU. CUP is affected more by the increased photosynthetic activity partially due to increased PAR, but not by timing of spring onset and autumn senescence of leaves. There is also significant ($p < 0.01$) reductions in emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), total nitrate ($HNO_3 + NO_3$) and ozone since 1992. The reductions in gaseous and particulate emissions imply the occurrence of direct aerosol mediated brightening and therefore increased PAR and enhanced C uptake by eastern North America mature forests.

1. Introduction

Accurate assessments of carbon (C) sources and sinks, and their distribution among terrestrial biospheres are imperative to better understand the global C cycle, to support the development of climate policies and to project the impact of future global change. Pan et al. (2011) recently found a large and persistent sink in world's forests amounting to a total forest sink of 2.4 ($\pm$0.4) Pg C year^{-1} globally for 1990 to 2007, using forest inventory data and long-term ecosystem carbon studies. However, due to several data gaps, the estimated terrestrial C sink, its size and location remain uncertain. Pan et al. (2011) estimates the net global forest C sink of 1.1 ($\pm$0.8) Pg C year^{-1} resides mainly in the temperate and boreal forests, consistent with previous estimates (Goodale and Aber, 2001; Sarmiento et al., 2010). One such area is the enhanced C sink of the New England forests, attributed to several explanations such as the enhanced C uptake due to: (1) the longer growing season, (2) the increased atmospheric CO_2 fertilization, (3) enhanced growth from increased nitrogen (N) deposition, and (4) forest regrowth.

It has been believed that the dominant sink mechanism of mature forests are the fertilizing effects of increased CO_2 concentrations in the atmosphere and the addition to soils of fixed nitrogen (N) from fossil-fuel burning and agricultural fertilizers. However, analysis of long-term free air CO_2 enrichment (FACE) observations of the change in biomass and growth rates suggests that such fertilization effects are much smaller than previously thought due to down-regulation of Rubisco activity and poor soil fertility (Hickler et al., 2008; Long et al., 2006). Nadelhoffer et al.

* Corresponding author at: University of Toronto, Department of Geography and Program in Planning, 100 St. George St., Room 5047, Toronto, ON, Canada M5S3G3. Tel.: +1 416 946 7715; fax: +1 416 946 3886.
E-mail addresses: gonsamoa@geog.utoronto.ca, ggalex2002@yahoo.com (A. Gonsamo).

http://dx.doi.org/10.1016/j.agrformet.2014.11.007
0168-1923/

(1999) show that N is not stimulating forest C uptake in temperate forests.

Traditionally, a longer growing season was attributed to an increase in C sequestration (Churkina et al., 2005; Desai, 2010; Dragoni et al., 2011; Keenan et al., 2014). But recent works indicate that the longer growing season due to climate warming has led to net loss of ecosystem C due to the prolonged period of autumn respiration and decline of snow water (e.g., Piao et al., 2008; Hu et al., 2010; Richardson et al., 2010; Wu et al., 2012a,b, 2013a,b). Due to challenges involved with estimating the slow senescence at the end of the growing season, most studies have previously focused solely on spring phenology. Recent findings have shown that not only autumn phenology, but also carbon uptake phenology can be estimated using remote sensing observations and CO_2 flux measurements (Gonsamo et al., 2013, 2012a,b; Gu et al., 2003, 2009; Wu et al., 2013a). Using these new land surface and carbon uptake phenology estimates, we study the phenological and environmental controls on C flux to answer as to why the eastern North America deciduous forests at the two longest-running flux tower sites in the region, Harvard Forest Environmental Monitoring and Borden Forest Research Station sites, despite being mature forests, their C sink strength is growing.

2. Materials and methods

2.1. Field sites

2.1.1. Harvard forest

The Harvard Forest Environmental Monitoring site (42°32′16″N and 72°10′17″W, 340 m elevation) is located in western Massachusetts, USA. The flux tower is located in a primarily deciduous temperate forest, about 110 km west of Boston, Massachusetts, USA. The vegetation is dominated by red oak (*Quercus rubra* L., 36% of basal area) and red maple (22% of basal area), with lesser quantities of other hardwoods (including black oak, *Quercus velutina* Lam., white oak, *Quercus alba* L., and yellow birch, *Betula alleghaniensis* Britton, totaling 15% of basal area) (Richardson et al., 2009). Conifers include eastern hemlock (13% of basal area), red pine (*Pinus resinosa* Aiton, 8% of basal area) and white pine (*Pinus strobus* L., 6% of basal area). The canopy height is approximately 20–24 m. Soils are mainly sandy loam glacial till with some alluvial and colluvial deposits. The climate is cool, moist temperate with daily mean air temperature of 8 °C. Annual mean precipitation is about 110 cm, and the precipitation is distributed approximately evenly throughout the year. Previous studies have shown the site to be strong sink for atmospheric C, with the annual C sequestration of 240 g C m^{-2} $year^{-1}$ (mean ± 1 SD) (Urbanski et al., 2007) based on eddy covariance measurements. The forest contained ∼100 Mg-C ha^{-1} in live aboveground woody biomass (AGWB) when the site was established. About 1/3 of the existing red oaks were established prior to 1895, another 1/3 prior to 1930, and the rest before 1940 (Urbanski et al., 2007); hence the stand is 82–117 years old. Although the stand was affected by a hurricane blowdown in 1938, many of the canopy trees now present would have already been established in the understory. Nearly continuous forest extends for several km northwest, west and southwest of the tower, the predominant wind direction.

2.1.2. Borden forest

The Borden Forest Research Station site (44°19′N, 79°56′W, 210 m elevation) is located in southern Ontario, Canada. The flux tower is located in a mixed hardwood and coniferous forest, about 80 km northwest of Toronto, Ontario, Canada. The vegetation is dominated by red maple (*Acer rubrum* L., 52.2% stem count), eastern white pine (*Pinus strobes* L., 13.5% stem count), large-tooth aspen (*Populus grandidentata* Michx., 7.7% stem count), White ash (*Fraxinus americana* L., 7.1% stem count), american beech (*Fagus grandifolia*, 5.6% stem count), with lesser quantity of other overstorey species (including eastern hemlock (*Tsuga canadensis*), trembling aspen (*Populus tremuloides* Michx.), red ash (*Fraxinus pennsylvanica*), black cherry (*Prunus serotina* Ehrh.), red pine (*P. resinosa*), american *elm* (*Ulmus americana* L.), sugar maple (*Acer saccharum*), yellow birch (*B. alleghaniensis*), choke cherry (*Prunus virginiana*), 14% stem count) (Teklemariam et al., 2009). The canopy height is about about 22 m tall on average. The forest soil is sand loamy. The climate is characterized by snow covered winter and humid continental climate with warm summer. Annual mean precipitation is about 79 cm, and the daily mean air temperature of 7 °C. The living tree stem density is 0.30 m^{-2} (2996 trees ha^{-1}) while tree biomass is 25.1 Mg ha^{-1} (Teklemariam et al., 2009). Living and dead trees together accounted for 0.41 m^{-2} (4137 trees ha^{-1}) with the dead trees (standing or fallen but not fragmented) accounting for about 27% of this total. The forest is natural re-growth from abandoned farm land which is approximately 100 years old (Lee et al., 1999). The available forest fetch of the flux tower is about 4.3 km to the south, and 3 km to the southwest. Outside of this range was predominantly grass and cropland.

2.2. CO_2 flux and meteorology variables measurements

The eddy-covariance technique is used to measure fluxes of CO_2, momentum, and sensible and latent heat at 30 m and 33 m at Harvard and Borden forest sites, respectively. The Harvard site data were downloaded from Harvard Forest Data Archive/Exchange web portal (ftp://ftp.as.harvard.edu/). Daily measurements are calculated from the half-hourly readings of covariance of the fluctuations in vertical wind speed and CO_2 concentration. Half-hourly flux values are excluded from the analysis in the case of instrument malfunction or if half-hour sample periods are incomplete. Nighttime flux values are excluding from analysis if the friction velocity (u^*) is below a threshold that varied among years. The net ecosystem exchange (NEE) measurements from 1992 to 2011 and 1996 to 2012 were used in this study for Harvard and Borden forest sites, respectively. Data for year 2004 for Borden forest site was excluded from analysis due to prolonged missing observations. We use the term net ecosystem productivity (i.e., NEP = −NEE) throughout the paper to indicate the net C balance of the site. Ecosystem respiration (R) is calculated from eddy covariance data during the night and outside the growing season, gap filled based on soil temperatures. Gross primary productivity (GPP) is estimated as difference between NEE and R. We used daily time integrated and gap filled GPP, R and NEP data for all dates of studied years. Daily data of gap filled air temperature and photosynthetically active radiation (PAR), the integrated incidence solar radiation from 400 to 700 nanometers, were also included in this study to study.

2.3. Land surface and carbon uptake phenology

Two distinct procedures were used each to retrieve the land surface phenology (LSP) and carbon uptake phenology (CUP) dates from GPP and NEP measurements, respectively (Fig. 1). LSP, defined as the study of the timing of recurring seasonal pattern of variation in vegetated land surfaces observed from synoptic sensors (Gonsamo et al., 2012b), was estimated from the daily GPP measurements based on double logistic curve fitting algorithm (Gonsamo et al., 2012a, 2013). The key LSP dates used in this study include the start of growing season (SOS), end of growing season (EOS), length of growing season (LOS). For the LSP determination